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High-Yield Neutron Activation System for the National Ignition Facility

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ABSTRACT (LA-UR-00-1670)

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The total fusion energy production from inertial confinement fusion targets at the National Ignition Facility (NIF) will be measured by a variety of fusion product diagnostics. Possibly the most accurate and precise determination of the total neutron yield over extreme dynamic range comes from radioactivity produced by threshold nuclear reactions in small samples placed near the target and then subsequently removed to count the gamma-ray activation. Such techniques have achieved ±7% (one-sigma) accuracy on magnetic fusion devices such as TFTR[1] and JET, and have demonstrated dynamic range between shots of over six-orders-of-magnitude.[2]

The high-yield system for NIF uses thin elemental samples ("foils") for which the gamma-ray detection efficiency can be calculated accurately from first principles. Then using dosimetric cross-sections and standard nuclear physics parameters the measured fluence can be determined and turned into total yield using neutronics modeling of the target chamber. Such a system can work down to 10^6 neutrons/cm^2 which, assuming a 50-cm exclusion radius, means minimum yields of ~3×10^{10} neutrons/shot. By increasing the sample distance to near the target chamber wall (4 meters), reducing the sample mass and increasing the counting rate, yields up to the maximum allowable on the system can be measured. A complementary low-yield activation system[3] will use larger masses to achieve higher sensitivity and will use associated particle methods[4] at an accelerator to determine the calibration. The system design requirements will be detailed for the high-yield neutron activation system on NIF. A pneumatic transport system similar to that used on TFTR and designed for ITER[5] will be described as well as the requirements for the irradiation ends and counting system.

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[1] Cris W. Barnes et al., Fusion Technology, 30 (1996) 63.

[2] Cris W. Barnes et al., Rev. Sci. Instrum 66 (1995) 888.

[3] C. L. Ruiz, these proceedings.

[4] C. L. Ruiz et al. Rev. Sci. Instrum. 63 (1992) 4889

[5] Cris W. Barnes et al., Rev. Sci. Instrum. 68 (1997) 577; Cris W. Barnes et al., in Diagnostics for Experimental Thermonuclear Fusion Reactors 2, edited by Stott et al., Plenum Press, New York, 1998, pg.479.

Dynamic Range and Accuracy Needed in Measuring Fusion Energy Production

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- TFTR achieved 6 orders dynamic range in DT neutron production (fusion power) with ±7% (one-sigma) accuracy.
- Future experiments will need even more:
  - ITER: DD ohmic to 1.5 GW plasmas
  - NIF: 10^{10} n/shot (physics tests) to 10 MJ ignition $\Rightarrow$ >8 orders of magnitude
- High accuracy of absolute calibration still desired.
- NIF
  - 30 MJ $\Rightarrow$ 10^{19} neutrons, $3\text{x}10^{12}$ n/cm^2 at vacuum vessel
  - 10^{10} neutrons/shot (hydro studies) $\Rightarrow$ $3\text{x}10^5$ n/cm^2 @ 50 cm (~minimum distance* and fluence)
  - The upper range is like TFTR; for accuracy, the low range requires up close and/or large masses calibrated as in present techniques by associated particles.

*N. Landen, "NIF diagnostic damage and design isuues", Technical Report UCRL-ID-134644, LLNL, 1999

Neutron Activation Provides Dynamic Range, Accuracy, and Precise Linearity

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- >8 orders of magnitude with precision and high accuracy is tough!
- There are many problems with doing this with "active" detectors on device.
- Neutron activation techniques, with its active detectors in low background counting lab, can achieve this, though not without care.
- At the same time, neutron activation can provide an accurate absolute calibration.

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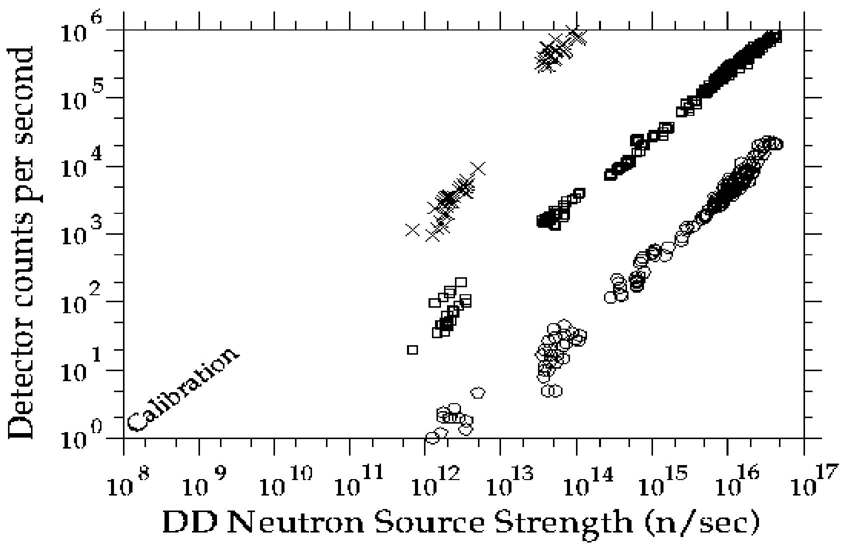
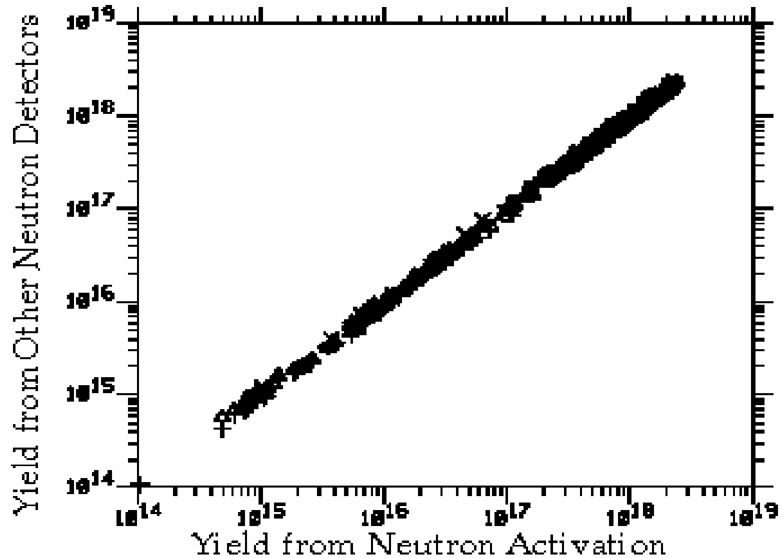
Example of linearity requirements from TFTR experience

Fission chambers should have efficiency about factor of 25 apart for cross-calibration of counting mode.



Neutron activation, where detector operates near same count rate as during calibration, is linear standard.



- Problems of linearity in active detectors
  - Count mode: deadtime, pileup, discriminator drift
  - Current mode: non-linear electronics
  - It is preferable to run detector in count mode at rate similar to rate during calibration.

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Activation can achieve dynamic range with precise linearity

- Count rate
  - can vary count rate (and inverse counting time) to maintain same counts and statistical error (factors of 10^4).
  - can move sample away from gamma-ray detector.
  - can calibrate electronic detectors with absolute source at various count rates.
- Mass (can change by factors of $\sim 10^2$)
- Distance to plasma source: can't change in MFE; can design large r^2 change in ICF (factor of >64)
- Exposure time limited by transit duration
- short half-lives only marginally effective
- low cross-sections not dosimetric, can be dominated by thermal or other reactions.

Limits on changing sample mass

- low mass
  - mass measurement accuracy
  - contamination
- high mass
  - gamma-ray self-attenuation (few cm attenuation lengths depending on energy) *
  - efficiency calculation, including distributed source
  - neutron self-absorption is minimal and calculable.
- (Can get around high mass limit with associated particle technique.)

*(55%-60% normal efficiency for Carlos' sized samples)

Past Experience with Fusion Energy Measurements Over Large Dynamic Range

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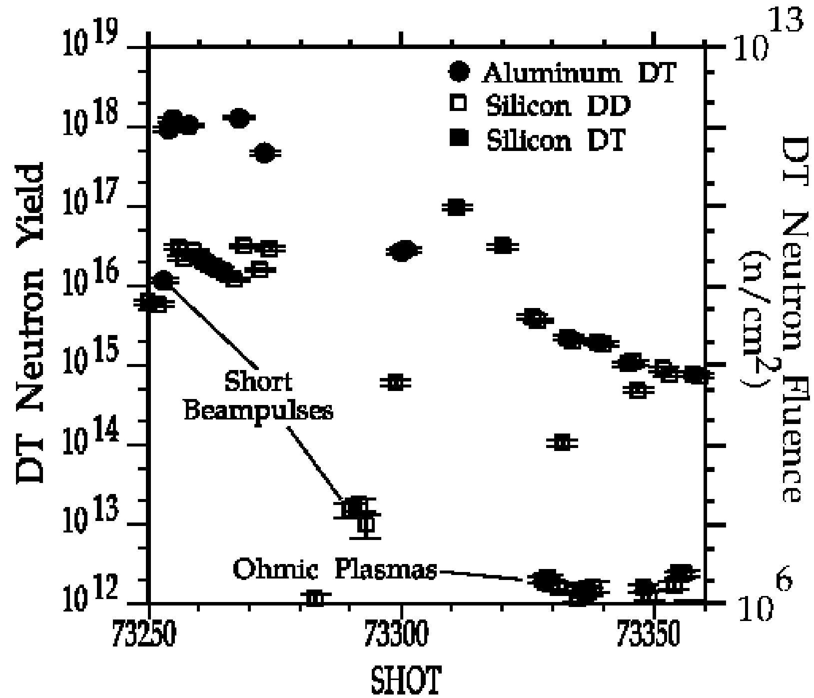
- TFTR
  - triton burnup and recyling tritium in ohmic plasmas ⇒ 10^{12} neutrons, 10^{6} n / cm^{2}
  - 10 MW ⇒ >10^{18} neutrons, 10^{12} n / cm^{2}
- JET
  - similar range achieved during PTE



From Barnes, Larson, LeMunyan, and Roquemore, *Rev. Sci. Instrum* **66** (1995) 888.

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The are two complementary approaches to absolute calibration of activation systems that will both be used for NIF

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FIRST PRINCIPLES & NEUTRONICS*

- Need absolutely known standards:
  - Balance for mass
  - Nuclear coefficients (isotopic abundance, branching ratios, half-lives)
  - Cross-section ("dosimetric")
  - Full-energy efficiency for detecting gamma-rays
    - » need thin foils or a radioactive sample "similar" to activation mass.
- Activation provides fluence calibration; we care about yield
  - Yield-to-fluence in MFE devices has succumbed to careful neutronics modeling of irradiation locations close to plasma:
    - » JET: two independent neutronics models
    - » TFTR: comparison to in-situ generator benchmark (±20%) or other detectors (±15%)
    - » JT60U: comparison in absolute sense to fission chamber nv characteristics.
  - We desire a low contribution from scattered neutrons.

*Cris W. Barnes *et al.*, *Fusion Technology*, **30** (1996) 63.

ASSOCIATED PARTICLE*

- Can use "associated particle" techniques to calibrate neutron response compared to 100% detection of associated charged particle in accelerator experiment.
- At high end (low fluence) with large mass, associated particle techniques are used to extend absolute calibration using large masses.
- A fluence from accelerator close to that obtained in measurement on fusion device is desired --- difficult to do at ignition power levels.
- Can calibrate absolutely at low fluences, and "rely" on linearity of other detectors to high fluence

C. L. Ruiz *et al.* *Rev. Sci. Instrum.* **63** (1992) 4889

Standards for "Absolute Calibration"

- What constitutes an "absolute" calibration for neutrons --- what is the "standard"?
  - Chemistry at ORNL (or equivalent) for ^{252}Cf, PuBe...
  - Dosimetric cross-section such as $^{27}Al(n,\alpha)^{24}Na$
  - DD or DT generators (oil-well logging industry, 10^8- 10^{10} n / sec), calibrated using activation cross-section
  - Mixed gamma-ray sets for activation
  - "100%" efficient detector of associated particles
- These provide an absolute reference at one fluence; then one needs linearity to match the measurement on the fusion device.

Neutronics Calculations of Fluence-to-Yield can be Accurate

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- Activation provides fluence calibration; we care about yield.
- Yield-to-fluence in MFE devices has succumbed to careful neutronics modeling of irradiation locations close to plasma:
  - JET: two independent neutronics models
  - TFTR: comparison to in-situ generator benchmark (±20%) or other detectors (±15%)
  - JT60U: comparison in absolute sense to fission chamber nv characteristics.
- ICF problem on NIF should be much simpler:
  - Point source of neutrons in ICF device
  - Need uniform (and hopefully thin) material between plasma and tally
  - Be away from "walls" to minimize back-scatter
  - Good agreement for widely different thresholds provides confidence
  - High-Yield system technique allows for inclusion of neutron energy dependent cross-section effects in calibration

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Other Possible Yield Diagnostics

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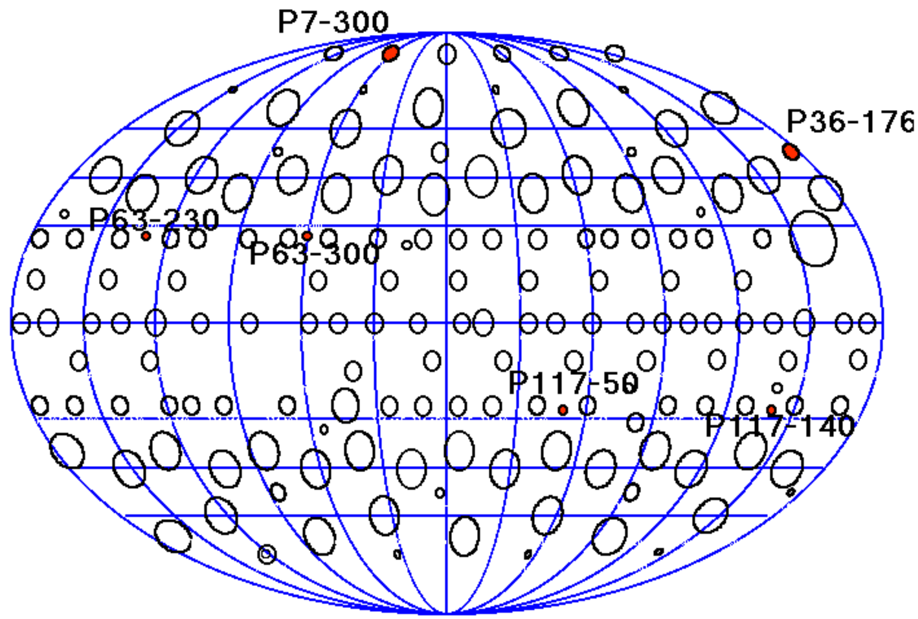
- Current mode detectors at different distances (nTOF or relatives) provide immediate read-out
  – Linearity maintained and checked relative to activation system (important but time-consuming job….)
- Proton-recoil spectrometer
  – Uses known proton recoil cross-section in thin plastic foil

Data from different positions on target chamber important for cross-calibration and looking for anisotropies

- “Total Neutron Yield” and “High-Yield” systems expecting to share pneumatic transport system.
- At least two irradiation ends at roughly “equivalent” polar angle theta but different azimuthal angle phi are needed for cross-calibrations.
- Data from different azimuthal angles (representing pole, equator, and in-between of implosion) should be taken to look for possible (but unlikely) emission anisotropy or spectrum changes.



Conceptual Design of Irradiation End

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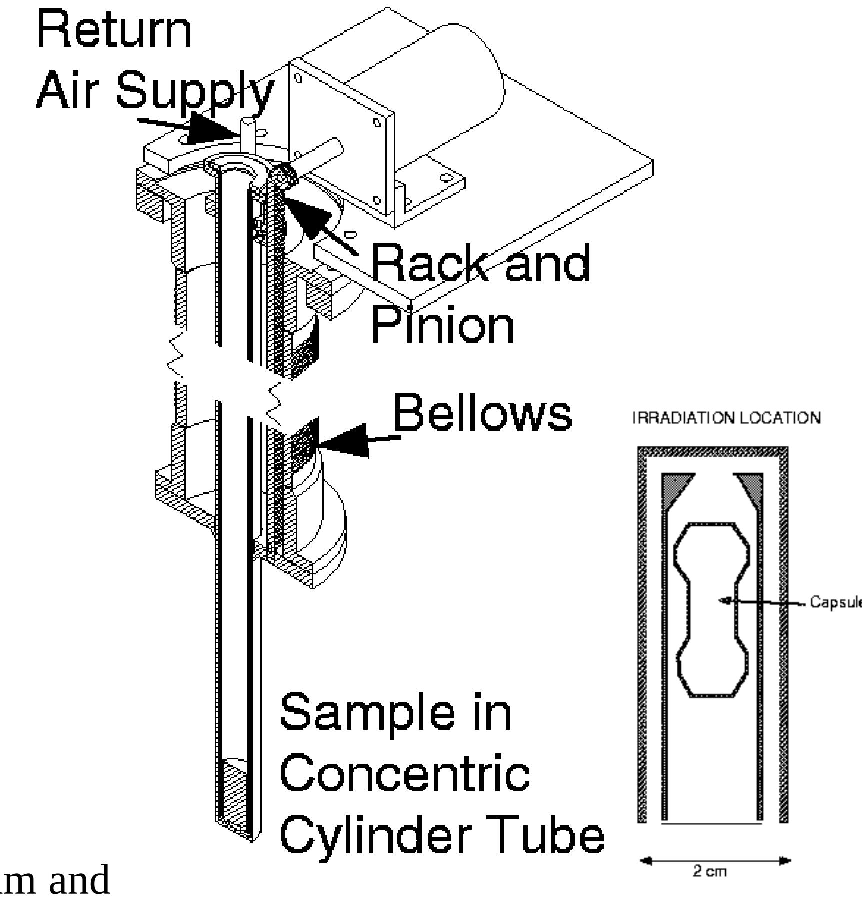
- Concentric cylinder irradiation end (as used on TFTR and proposed for ITER).
- Irradiation end mounted on bellows with rack and pinion encoded to position before shot from close to target (50 cm or less) or out at 4 m (1 m in from wall).
- Pressure drop when capsule reaches end makes good radiation insensitive signal.
- Initial proposal to use 1" I.D. tubing and TFTR-size capsules* with about 10 inch minimum radius of curvature.
- Consideration for double encapsulation of liquid samples needed.



*0.75" I.D. of capsule would mean 21 g Indium and 26 g copper to make 1 cm long sample with 55%-60% gamma-ray efficiency compared to thin foil.

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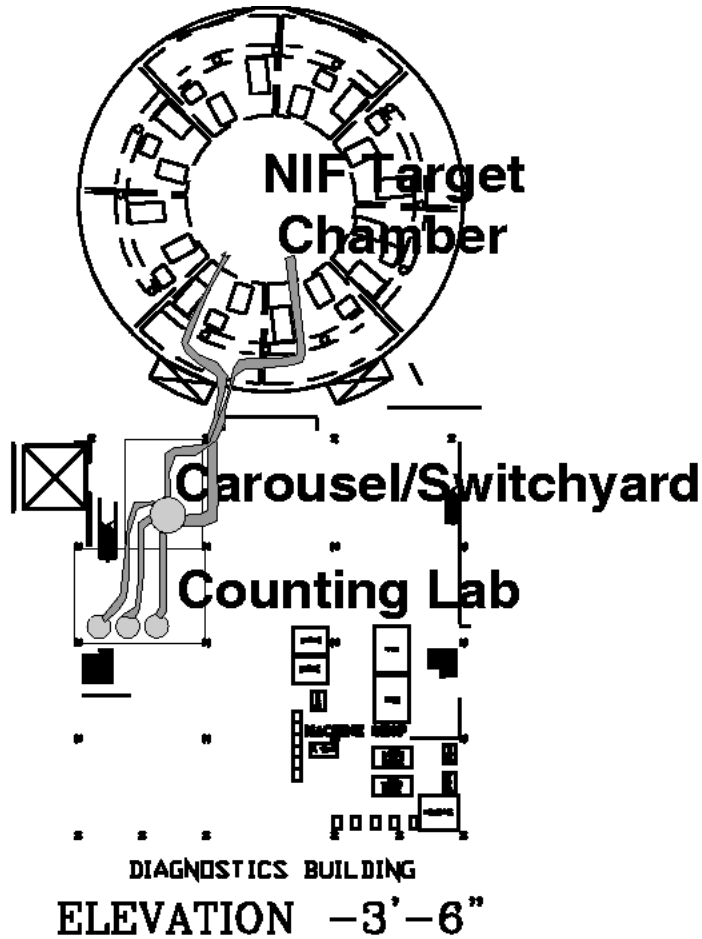
Capsules routed through Carousel / Switchyard to Counting Lab

- Propose to use JET-like multi-in multi-out "carousel" to achieve maximum system flexibility with simplicity.
- Carousel/Switchyard room provides holding area for radioactive materials.
- Separate Counting Lab holds low background HPGe detector, high-efficiency HPGe well detector, robust large NaI detectors, and NaI coincidence system.
- A separate small material storage and sample preparation are is also needed.



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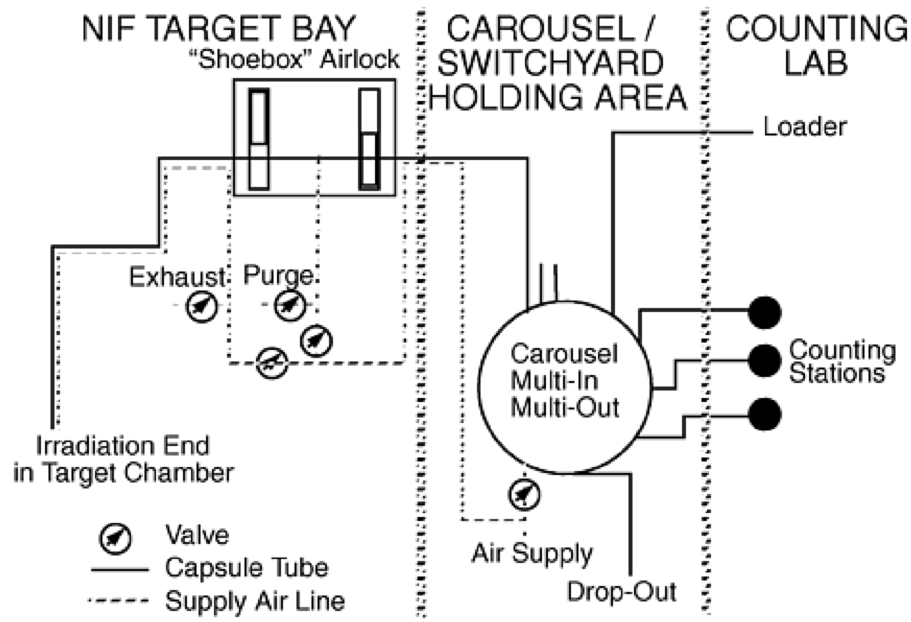
Pneumatic Transport System Allows Flushing of Activated Air and Flexible Routing of Capsules

- At high-yields the very air inside the pneumatic transport system gets activated and must be purged.
- "Shoebox" airlocks for each irradiation end mounted on target bay way where pneumatic lines leave bay.



SUMMARY

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- The system design requirements for the High-Yield Neutron Activation System for the National Ignition Facility are presented, and a conceptual design to meet those requirements is described.
- Feedback from the community is needed to insure requirements are sufficient.
- Future critical issues are:
  - To begin MCNP modeling of the system, and
  - To work on improvements to precision of placement of samples by the pneumatic system, especially with respect to the counting detectors.

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